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Abstract

Northern Eurasia is made up of a complex and diverse set of physical, ecological, climatic and human systems, which provide important ecosystem services including the storage of substantial stocks of carbon in its terrestrial ecosystems. At the same time, the region has experienced dramatic climate change, natural disturbances and changes in land management practices over the past century. For these reasons, Northern Eurasia is both a critical region to understand and a complex system with substantial challenges for the modeling community. This review is designed to highlight the state of past and ongoing efforts of the research community to understand and model these environmental, socioeconomic, and climatic changes. We further aim to provide perspectives on the future direction of global change modeling to improve our understanding of the role of Northern Eurasia in the coupled human–Earth system. Modeling efforts have shown that environmental and socioeconomic changes in Northern Eurasia can have major impacts on biodiversity, ecosystems services, environmental sustainability, and the carbon cycle of the region, and beyond. These impacts have the potential to feedback onto and alter the global Earth system. We find that past and ongoing studies have largely focused on specific components of Earth system dynamics and have not systematically examined their feedbacks to the global Earth system and to society. We identify the crucial role of Earth system models in advancing our understanding of feedbacks within the region and with the global system. We further argue for the need for integrated assessment models (IAMs), a suite of models that couple human activity models to Earth system models, which are key to address many emerging issues that require a representation of the coupled human–Earth system.

1. Introduction

Northern Eurasia consists of a diverse set of ecosystems, both natural and managed, across a wide range of climatic conditions, including subarctic, humid continental, semi-arid and desert climates. The region is host to a variety of the Earth's biomes like tundra, taiga, broadleaved forest, steppe and desert, as well as significant areas of cropland, pasture, rangeland, managed forests and urban areas. Northern Eurasia includes roughly 70% of the Earth's boreal forest and is underlain by more than two-thirds of the Earth's permafrost (Groisman *et al* 2009). Frozen soils within the northern Arctic and subarctic regions store large quantities of organic carbon, whether in the top soil layer or in deposits deeper than 3 m (McGuire *et al* 2009, Schuur *et al* 2015). For example, large amounts of carbon are believed to be sequestered in the deep permafrost carbon pool of the Yedoma region in Siberia, in typical Yedoma deposits (late Pleistocene ice- and organic-rich silty sediments) in Alaska, and in deposits formed in thaw-lake basins (generalized as thermokarst deposits). Similarly, significant stocks of carbon are stored in boreal forests, both in their soil, live biomass, deadwood and litter (Pan *et al* 2011, Thurner *et al* 2014). As a result, Northern Eurasia is a major player in the global carbon budget. Furthermore, the region has experienced major environmental and socioeconomic changes over the past century. These include increases in temperature, growing season length, floods and droughts (Groisman and Soja 2009, Soja and Groisman 2012, Groisman *et al* 2009), permafrost thaw (Romanovsky *et al* 2007), and forest fires (Groisman *et al* 2007); changes in snow characteristics and icing conditions (Bulygina *et al* 2011, 2015); and extensive disturbance from land-use change and water management projects (Groisman *et al* 2009). These past and ongoing environmental and socioeconomic changes can have major impacts on biodiversity, environmental sustainability, ecosystem services, and the carbon cycle in the region that can potentially feedback to alter the global Earth system. These studies also suggest the region is poised to be further impacted by future climate change. For these reasons, Northern Eurasia represents a critical and complex region to understand with substantial challenges for the modeling community.

To better understand this region, which extends from 15°E in the west to the Pacific coast in the east and from 40°N in the south to the Arctic Ocean coast in the north, a group of international scientists, including US, European, Asian and Russian scientists have been motivated to work together and developed a program of research called the Northern Eurasia Earth Science Partnership Initiative (NEESPI). As a result of the first formal NEESPI workshop, which took place in 2002, and other subsequent workshops, the mission of NEESPI was defined as follows: '. . . identify the critical science questions and establish a program of coordinated research on the state and dynamics of terrestrial ecosystems in Northern Eurasia and their interactions with the Earth's climate system to enhance scientific knowledge and develop predictive capabilities to support informed decision-making and practical applications.' An overview of the NEESPI science plan is given in Groisman and Bartalev (2007). Since then, a substantial effort has been directed to the development of a variety of models to organize and improve our knowledge of Earth system processes in Northern Eurasia, especially focusing on their future responses to climate change and changes in socioeconomic drivers. Through NEESPI, a large body of interdisciplinary and dynamic research has been produced, highlighting major implications of environmental, socioeconomic and climatic change for natural and managed ecosystems and investigating the potential future states of the region to support informed decision-making for society. Many of these results were published in three completed Focus Issues in *Environmental Research Letters* (Groisman and Soja 2007, 2009, Soja and Groisman 2012), an ongoing Focus Issue (which will be the last NEESPI Focus Issue), one completed Special Issue in *Global and Planetary Change* (Groisman 2007) and a large number of books (Groisman *et al* 2014).

In this review paper, we assess the state of recent and ongoing efforts to model specific aspects of the Earth system relevant to Northern Eurasia. Specifically, we survey articles from the various NEESPI special issues, other NEESPI-supporting articles and articles selected based on the authors' experience and knowledge with the relevant literature on Northern Eurasia. We further select the articles describing the development and application of models or modeling frameworks to investigate issues specific to the region. We underscore the few studies that have aimed to integrate multiple components of the Earth system and frame the NEESPI modeling efforts in the context of more global and general modeling exercises. We then discuss new approaches to global change modeling for Northern Eurasia. We draw attention to the usefulness of Earth system models to examine the potential importance of feedbacks among Earth system components on the evolution of global change and the responses of ecosystems, including those in Northern Eurasia, to that change. We further emphasize the need to incorporate human dimensions with environment dynamics and the emergence of integrated assessment models as important tools to model the coupled human–Earth system. A wide spectrum of model integration exists, ranging in complexity from representing the impact of climate change on a single component of the Earth system to a fully integrated coupled human–Earth system modeling framework (see figure 1). However, issues still exist, consequently NEESPI researchers need to develop a new paradigm of integrated global change modeling for Northern Eurasia. Finally, we discuss how new modeling efforts may help to provide insights into emerging issues unique to the region and address questions of uncertainty in future projections.

2. Recent and ongoing modeling studies over Northern Eurasia

A large number of models have been developed to represent the complex and diverse set of physical, ecological, climatic and human systems that make up Northern Eurasia. These include models focusing on the many ecological and geophysical processes comprising Earth system dynamics of interest in the region, such as the hydrological cycle, soil thermal dynamics, wildfires, dust emissions, carbon cycle, terrestrial ecosystem characteristics, climate and

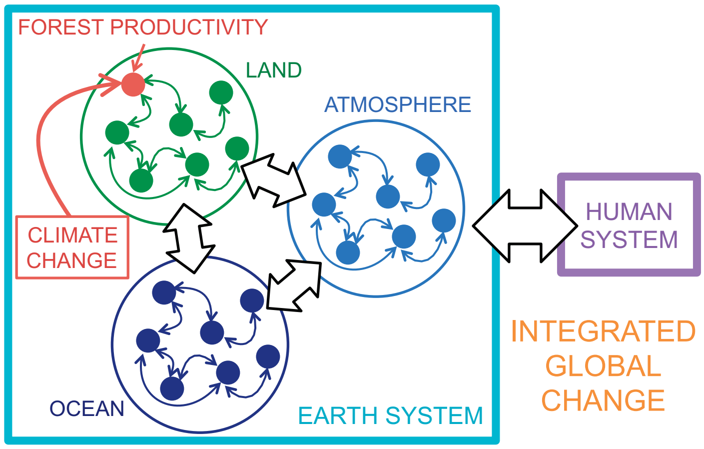

Figure 1. Schematic showing an example of a current study that focuses on the climate impacts on a single component of the Earth system, here imposing climate change on forest productivity (shown in red), compared to an example of a framework that links the Earth system (cyan), including the land (green), atmosphere (light blue) and ocean (dark blue) and their individual components, to the human system (purple). The resulting coupled human–Earth system modeling framework allows for a complete investigation of integrated global change. There is a spectrum of integrated modeling studies, and most studies fall in between these two drastic examples (i.e. representing the impact of climate change on land processes, including both red and green colors).

weather, or sea ice. Modeling efforts also focus on human dimensions, like demographic models, risk management models, and models that link the human system and the Earth system, such as models representing agriculture, forestry and water management. Because Northern Eurasia accounts for 60% of the land area north of 40°N, includes roughly 70% of the Earth's boreal forest and more than two-thirds of the Earth's permafrost, most of the past and ongoing research on modeling of Earth system dynamics over Northern Eurasia have put a large emphasis on the land system, whether the focus is on physical processes (e.g. land and water carbon cycle, energy balance) or the fate of the land system under climate change (permafrost thawing, agriculture, wildfire, dust storms). Table 1 shows a non-exhaustive list of modeling studies with a focus on Northern Eurasia sorted by specific aspects of the Earth and human systems.

These models also vary widely in their characteristics, approaches, applications and focus, from *empirical models* that are based on statistical relationships using observed data to *process-based models* that focus on simulating detailed processes that explicitly describe the behavior of a system, and from *agent-based models* that simulate individual agents of a system in order to assess the behavior of the system as a whole to *systems models* that focus on the interactions among the various components of a system. Depending on the particular scope of the research question, models are developed to take advantage of the various model classes and approaches, as summarized in figure 2.

Empirical models can be expertly calibrated to reproduce past and current behavior of the system when observational data is available, but they can suffer from unimpressive out-of-sample performance, such as for future climate change studies, in different geographical regions, or for components with different properties. Process-based models are well-suited for examining a system's responses to evolving conditions, or when observational datasets are scarce or non-existent (i.e. gap-filling or re-analysis datasets), but they can suffer from biases, overfitting of parameters due to data scarcity, and a lack of consensus on the underlying theory to describe a specific process. For these reasons, empirical models are mainly used when sufficient observational datasets are available to derive robust statistical relationships, such as empirical crop models in the United States (Lobell and Asner 2003, Schlenker and Roberts 2009, Sue Wing *et al* 2015), but are not as commonly used over Northern Eurasia. Process-based models can be used in global studies, such as process-based crop models simulating yields over the entire globe, even in regions where crops are not currently growing (Rosenzweig *et al* 2014).

Agent-based models focus on a single agent, represented with a high level of detail, but at the cost of not representing interactions and feedbacks among the various components of the Earth system. These models are particularly common in ecology, such as modeling individual trees in a forest (Shuman *et al* 2013b). At the other end of the spectrum, systems models are generally designed to study feedback processes, with a simplified representation of each component, often assumed to be homogeneous in scale and properties, and thus are more commonly used at larger scales when computational demand is high and data is lacking. For example, micro-scale land surface models can use a multilayer structure to represent the canopy, even distinguishing leaf angle classes in each canopy layer to represent differential illumination of canopy surfaces (Xu *et al* 2014); meanwhile global land surface models generally assume a single layer 'big leaf' model (Friend 2001).

Table 1. Non-exhaustive list of modeling studies with a focus on Northern Eurasia sorted by specific aspects of the Earth and human systems. Note that some studies are listed under several aspects of the Earth and human systems.

Agriculture (crop modeling, economics)	Dronin and Kirilenko 2010, Gelfan *et al* 2012, Iizumi and Ramankutty 2016, Magliocca *et al* 2013, Peng *et al* 2013, Schierhorn *et al* 2014a, 2014b, Tchebakova *et al* 2011
Air quality (aerosols, ozone, pollen . . .)	Baklanov *et al* 2013, Darmenova *et al* 2009, Lu *et al* 2010, Siljamo *et al* 2013, Sofiev *et al* 2013, Soja *et al* 2004, Sokolik *et al* 2013, Xi and Sokolik 2015, 2016
Carbon (in land and water)	Bohn *et al* 2013 2015, Cresto-Aleina *et al* 2015, Dargaville *et al* 2002a, 2002b, Dass *et al* 2016, Dolman *et al* 2012, Gao *et al* 2013, Glagolev *et al* 2011, Gustafson *et al* 2011, Hayes *et al* 2011a, 2011b, 2014, John *et al* 2013, Kicklighter *et al* 2013, 2014, Kim *et al* 2011, Koven *et al* 2011, Kuemmerle *et al* 2011, 2011b, Lu *et al* 2009, McGuire *et al* 2010, Mukhortova *et al* 2015, Narayan *et al* 2007, Olchev *et al* 2009a, 2013, Rawlins *et al* 2015, Rossini *et al* 2014, Sabrekov *et al* 2014, 2016, Saeki *et al* 2013, Schaphoff *et al* 2015, Schierhorn *et al* 2013, Schulze *et al* 2012, Shakhova *et al* 2013, 2015, Shuman and Shugart 2009, Shuman *et al* 2013a, Yue *et al* 2016, Zhang *et al* 2012, Zhu *et al* 2013, 2014, Zhu and Zhuang 2013, Zhuang *et al* 2013
Climate	Anisimov *et al* 2013, Arzhanov *et al* 2012a, 2012b, Miao *et al* 2014, Monier *et al* 2013, Onuchin *et al* 2014, Shahgedanova *et al* 2010, Shkolnik and Efimov 2013, Volodin 2013, Volodin *et al* 2013, Zuev *et al* 2012
Cryosphere (snow, glaciers, sea ice . . .)	Callaghan *et al* 2011a, 2011b, Farinotti *et al* 2015, Hagg *et al* 2006, Klehmet *et al* 2013, Loranty *et al* 2014, Pieczonka and Bolch 2015, Shahgedanova *et al* 2010, Shakhova *et al* 2015, Sorg *et al* 2012
Demography	Heleniak 2015
Energy balance	Brovkin *et al* 2006, Gálos *et al* 2013, Loranty *et al* 2014, Olchev *et al* 2009b, Oltchev *et al* 2002b, Tchebakova *et al* 2012
Hydrological cycle	Bowling and Lettenmaier 2010, Cresto-Aleina *et al* 2015, Gelfan 2011, Georgiadi *et al* 2010, 2014, Hagg *et al* 2006, Karthe *et al* 2015, Khon and Mokhov 2012, Klehmet *et al* 2013, Kuchment *et al* 2011, Liu *et al* 2013, 2014, 2015, McClelland *et al* 2004, Motovilov and Gelfan 2013, Novenko and Olchev 2015, Olchev *et al* 2009a, 2013, Oltchev *et al* 2002a, 2002b, Osadchiev 2015, Rawlins *et al* 2010, Serreze *et al* 2006, Shiklomanov *et al* 2013, Shiklomanov and Lammers 2013, Sorg *et al* 2012, Streletskiy *et al* 2015, Troy *et al* 2012, Zhang *et al* 2011
Land-use change	Blyakharchuk *et al* 2014, Griffiths *et al* 2013, Gustafson *et al* 2011, Hayes *et al* 2011a, Hitztaler and Bergen 2013, Kicklighter *et al* 2014, Kraemer *et al* 2015, Kuemmerle *et al* 2009, Meyfroidt *et al* 2016, Robinson *et al* 2013, Schierhorn *et al* 2013, Schierhorn *et al* 2014, 2014b, Smaliychuk *et al* 2016, Zhang *et al* 2015
Infrastructure	Shiklomanov and Streletskiy 2013, Shiklomanov *et al* 2017, Stephenson *et al* 2011, Streletskiy *et al* 2012
Nitrogen	Kopáček *et al* 2012, Kopáček and Posch 2011, Oulehle *et al* 2012, Zhu and Zhuang 2013, Zhuang *et al* 2013
Permafrost	Euskirchen *et al* 2006, Gao *et al* 2013, Gouttevin *et al* 2012, Hayes *et al* 2014, MacDougall and Knutti 2016, Marchenko *et al* 2007, Shakhova *et al* 2013, 2015, Streletskiy *et al* 2012, 2015, Zhang *et al* 2011
Terrestrial ecosystems characteristics	Cresto-Aleina *et al* 2013, Kopačková *et al* 2014, 2015, Lapenis *et al* 2005, Lebed *et al* 2012, Li *et al* 2016, Shuman *et al* 2013, 2013b, Shuman and Shugart 2012, Ziółkowska *et al* 2014
Vegetation shifts	Gustafson *et al* 2011, Jiang *et al* 2012, 2016, Khvostikov *et al* 2015, Kicklighter *et al* 2014, Li *et al* 2014, Macias-Fauria *et al* 2012, Novenko *et al* 2014, Schaphoff *et al* 2015, Shuman *et al* 2015, Soja *et al* 2007, Tchebakova *et al* 2009, 2010, 2016a, 2016b, Tchebakova and Parfenova 2012, Velichko *et al* 2004
Weather (i.e. extreme events)	Barriopedro *et al* 2011, Meredith *et al* 2015, Mokhov *et al* 2013, Schubert *et al* 2014, Shkolnik *et al* 2012
Wildfire	Balshi *et al* 2007, Dubinin *et al* 2011, Gustafson *et al* 2011, Kantzas *et al* 2013, Loboda and Csiszar 2007, Malevsky-Malevich *et al* 2008, Narayan *et al* 2007, Park and Sokolik 2016, Schulze *et al* 2012, Soja *et al* 2004, Tchebakova *et al* 2009, 2012, Vasileva and Moiseenko 2013
Zoology	Kuemmerle *et al* 2011a, 2014, Ziółkowska *et al* 2014

Process-based models have been used most frequently by the NEESPI community, most likely because Northern Eurasia is not as data rich as other regions of the world. However, in practice, most process-based models include some form of empirical modeling to inform parameterizations of processes that are not precisely known or processes taking place at scales too small to be fully represented. Meanwhile many models fall in-between agent-based models and systems models, with a compromise made between the detailed representation of systems and their interactions. Furthermore, because of the trade-off between model complexity, scale and observational data availability, methodologies have been developed to combine models with observational datasets, whether they are based on inventories (Dolman *et al* 2012) or remote sensing (John *et al* 2013).

While most modeling studies focus on a specific component of the Earth system, a few studies have integrated various aspects of the Earth system, in terms of scale (Gouttevin *et al* 2012, Zhu *et al* 2014), teleconnection or global feedbacks (Dargaville *et al* 2002b, Macias-Fauria *et al* 2012) and processes (Euskirchen *et al* 2006, Callaghan *et al* 2011b, Sokolik

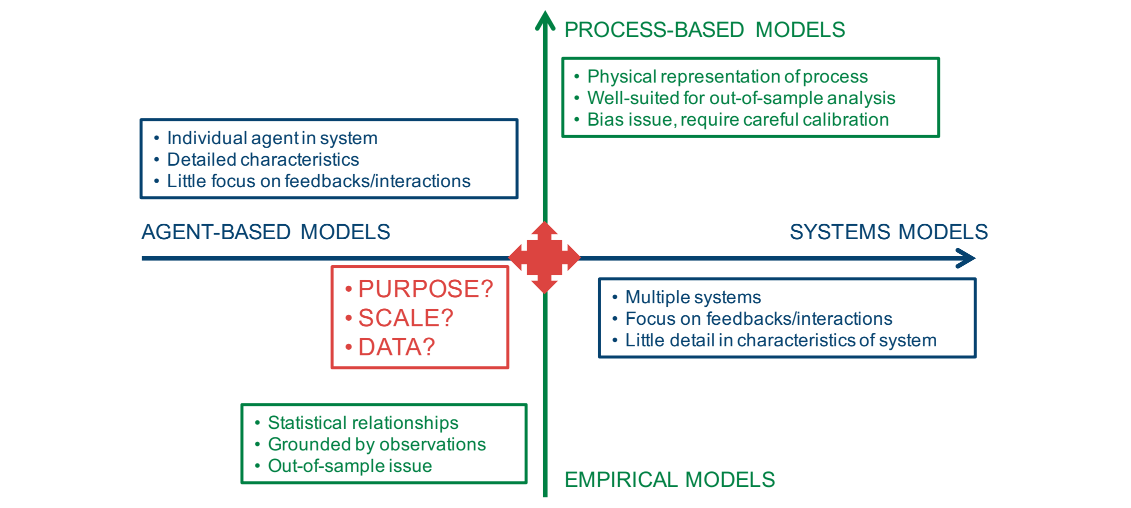

Figure 2. Schematic summarizing the strength and limitations of models based on the class of model (empirical models to process-based models) and modeling approaches (from agent-based models to systems models). The choice of model characteristics generally depends on the purpose, scale and data availability.

et al 2013). Other studies focus on integrated systems where multiple disciplines overlap, such as modeling studies of water management (Shiklomanov *et al* 2013), land management (Gustafson *et al* 2011, Kuemmerle *et al* 2011b, Lebed *et al* 2012, Robinson *et al* 2013, Shuman *et al* 2013a, Blyakharchuk *et al* 2014) or climate and infrastructure (Shiklomanov and Streletskiy 2013, Shiklomanov *et al* 2017). This growing effort to integrate existing models, through scale, processes and feedback has translated in more coordinated and multidisciplinary research projects. For example, NEESPI scientists have integrated models that can interact with each other, e.g. weather and aerosol physics, including dust and smoke aerosols (Darmenova *et al* 2009, Xi and Sokolik 2015, 2016, Park and Sokolik 2016); permafrost and terrestrial hydrology with water management (e.g. Zhang *et al* 2011, Shiklomanov and Lammers 2013); the carbon and water cycles (e.g. Bohn *et al* 2015); land carbon and atmospheric transport modeling (Dargaville *et al* 2002a, 2002b); and biospheric and climate information (Tchebakova *et al* 2009, 2016a, 2016b, Shuman *et al* 2015).

These modeling studies generally fall into two categories: (1) diagnostic modeling studies that identify key mechanisms and processes that control the behavior of a system, assess the present relationships among critical components of the environment and evaluate models based on experimental and observational datasets (e.g. Gouttevin *et al* 2012, Anisimov *et al* 2013, Zhu *et al* 2014, Rawlins *et al* 2015); and (2) prognostic modeling studies that focuses on the response of Earth system components to global change (Gao *et al* 2013, Zhu *et al* 2013, Kicklighter *et al* 2014).

Diagnostic modeling studies have improved our understanding of the Earth system. These studies are important as they ground the modeling efforts to reality and provide a critical sanity check. They also guarantee that models pass rigorous tests before being used to enhance our understanding of mechanisms and processes controlling the system of interest. For this purpose, there is a growing need for close collaborations between modeling groups and observational studies (Liu *et al* 2013, 2014, Loranty *et al* 2014, Rawlins *et al* 2015). Many approaches exist to evaluate models at different temporal and spatial scales. Focusing on the example of terrestrial carbon and water fluxes, eddy-covariance is used for local high temporal resolution (Liu *et al* 2014, 2015, Rawlins *et al* 2015); dissolved organic carbon (DOC) export and discharge at the mouth of a river allows for the assessment of the integrated response of a watershed (Kicklighter *et al* 2013); inventory of forest carbon stocks and biomass increment at the regional-to-global scale evaluation (Pan *et al* 2011); or satellite measurements for spatially explicit regional-to-global scale evaluation (Liu *et al* 2013, 2014, Mehran *et al* 2014, Rawlins *et al* 2015).

At the same time, if a model is assessed as performing realistically when simulating past or present day conditions, it does not guarantee that the response to different environmental conditions, like future climate change, is sensible. For this reason, suitable formalisms and standard experimental protocols that allow comparison between models are getting more traction. The number of Model Intercomparison Projects (MIPs) has grown substantially in the past decade. With the inception of the Atmospheric Model Intercomparison Project (AMIP) in 1990, more than 30 MIPs are now in existence, including the Snow Models Intercomparison Project (SnowMIP), the Ocean Carbon-Cycle Model Intercomparison Project (OCMIP), or the Arctic Regional Climate Model Intercomparison Project (ARMIP) to name a few. A list of MIPs can be found at www.wcrp-climate.org/wgcm/projects.shtml. Most MIPs usually include models that are structurally similar and that

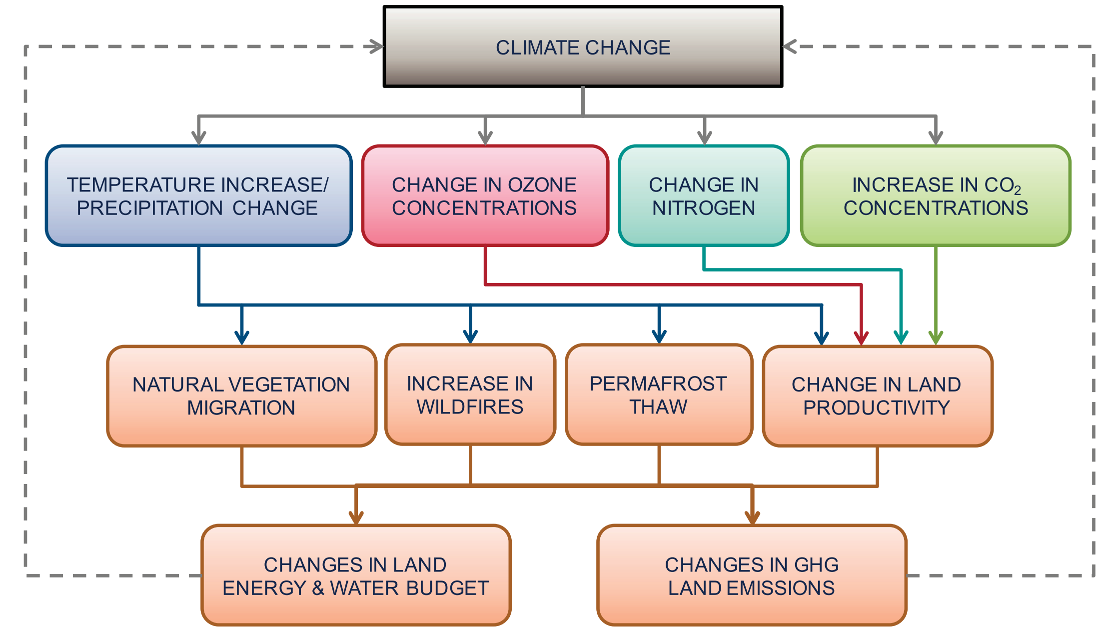

Figure 3. Schematic of a detailed, but non-exhaustive, accounting of climate change impacts on land biogeochemistry and biogeophysics. Dashed lines represent the potential feedback of terrestrial ecosystem responses to the climate system.

focus on the same component of the Earth system (Sea-Ice Model Intercomparison Project, SIMIP), phenomenon (Tropical Cyclone Climate Model, TCMIP), process (Cloud Feedback Model Intercomparison Project, CFMIP), time period of focus (Paleo Model Intercomparison Project, PMIP) or on the interaction among specific components of the Earth system (Atmospheric Chemistry and Climate Model Intercomparison Project, ACC-MIP). Because of large inconsistencies in input datasets, model output, or experimental design of simulations between different classes of models, most models within a MIP have the same structure and generally fall in the category of process-based models. Little effort has been devoted to comparing different classes of models (process-based versus empirical; agent-based versus system models). Similarly, few MIPs have focused on a region of interest, especially on Northern Eurasia.

Prognostic modeling studies focus on projections of climate change over Northern Eurasia (Arzhanov *et al* 2012a, 2012b, Shkolnik *et al* 2012, Monier *et al* 2013, Volodin *et al* 2013) and its associated impacts over the 21st century. These studies build upon the model development and evaluation discussed previously and they investigate the response of the Earth system to global change. They often focus on specific processes, such as permafrost thaw (Gao *et al* 2013) or natural plant migration (Jiang *et al* 2012, 2016), or specific elements of the Earth system, like agriculture (Schierhorn *et al* 2014a, 2014b) or forests (Tchebakova and Parfenova 2012, Olchev *et al* 2013). While highly focused modeling studies can greatly enhance our understanding of the response of a key process or element of the Earth system, they usually make it difficult to assess the behavior of a system as a whole. For example, there are many processes through which climate change can impact the emissions of greenhouse gases from the land system (see figure 3), including: (1) climate-induced vegetation shifts; (2) changes in the frequency and severity of wildfires; (3) permafrost thaw; and (4) changes in land productivity caused by changes in temperature and precipitation, ozone damage, nitrogen deposition, CO_2 fertilization, and land management. Individually, a study focusing on a single process can enhance our understanding of the land biogeochemistry under future climate change, such as the work of Felzer *et al* (2005), which focuses on the role of ozone damage on forestry and crop productivity. But unless such studies are well coordinated (e.g. using the same climate change scenarios) and integrated (using the same modeling framework), these studies would not permit a detailed accounting and an attribution of the relative role of each process in the overall system.

Furthermore, if interactions and feedbacks exist among the different processes of climate change impacts, individual studies could be misleading. For example, changes in land emissions of greenhouse gases (GHGs) can lead to potentially significant feedbacks to the climate system, adding to the anthropogenic emissions, and leading to even greater concentrations of greenhouse gases in the atmosphere. While our example focuses on land biogeochemistry, the impact of climate changes in the characteristics of the land, including albedo, surface roughness and soil moisture (biogeophysical impact) plays an equally important role in how the Earth's energy budget may evolve (Brovkin *et al* 2006, 2013). As a result, we argue that a greater understanding and comprehensive representation of feedbacks and interactions within the Earth system are required and should be a major emphasis of future model development efforts.

Most studies of climate change impacts rely on standard scenarios of climate change, such as climate model projections archived from the Coupled Model Intercomparison Project Phase 5 (CMIP5, Taylor *et al* 2012) that use the Representative Concentration Pathway (RCP) scenarios (van Vuuren *et al* 2011a). These climate scenarios are part of the latest Intergovernmental Panel on Climate Change (IPCC) Assessment Report (AR5) and have the advantage of being the result of an international coordinated effort to create multi-model ensembles of climate simulations under a set of standard scenarios of greenhouse gas concentrations. Such ensembles of climate simulations sample the model structural uncertainty that arise from differences in the parameterizations of climate processes, the climate system response and resolution; however, they are only an ensemble of opportunity and do not sample the full range of projections. Nonetheless, multi-model ensembles based on coordinated scenarios have become the standard for the climate impacts research community, and have resulted in major advances in the understanding of many components of the Earth system, including ocean ecosystems, agriculture, the global climate system response, climate extremes, the Asian monsoon, Arctic sea ice, or soil carbon (Bopp *et al* 2013, Kharin *et al* 2013, Knutti and Sedláček 2013, Rosenzweig *et al* 2014, Sperber *et al* 2013, Stroeve *et al* 2012, Todd-Brown *et al* 2013). A common experimental design for studies modeling climate impacts is to prescribe climate change using the CMIP5 multi-model ensembles, either the full ensemble including all models that provide the relevant climate information or simply a subset of models, and to examine the varied response of a particular component of the Earth system. A limitation of such a modeling framework is that because climate change is prescribed, little attention is placed on potential feedbacks, such as the regional and global land feedbacks described in figure 3, which are largely absent from the CMIP5 multi-model ensembles. The reliance of standardized climate scenarios can often result in a lack of systematic analysis of the various feedbacks in the climate system. As a result, it is still unclear which feedbacks are important and need to be considered. The alternative is to use modeling frameworks that are able to represent the many feedbacks in the Earth system, both at the global and regional scales. Such models, known as Earth system models, are expected to be important tools for future modeling studies focusing on Northern Eurasia.

3. New approaches to global change modeling for Northern Eurasia

While many studies focus on the impact of climate change on various ecosystems and components of the Earth system, climate change impacts cannot be examined without considering the role of human activity. For this reason, we argue that the term 'climate change' should be replaced by the more accurate terminology of 'global change'. To examine how global change influences the Earth system, two related approaches are being developed based on an integrated modeling framework, Earth system models and integrated assessment models. Below, we first describe these two integrated modeling frameworks in general and the motivations behind them. We then describe the potential benefits of applying these approaches to Northern Eurasia along with the data needed and available to support such modeling activities.

3.1. Earth system models

The Earth system has complex interactions among various physical, biological and chemical processes in its different components such as the land, the atmosphere and the ocean. An exact definition of the Earth system is not formally agreed upon. In this review, we offer the following definition: coupled atmosphere, ocean, land (including rivers and lakes) and cryosphere (sea ice, land ice, permafrost) components with a representation of dynamical and physical processes (e.g. river flow, ocean eddies, cloud processes, erosion), chemical processes (chemical gases and aerosols), biogeochemical processes (life-mediated carbon-nutrient dynamics) and biogeophysical processes (life-mediated water and energy balance) in all components.

Earth system models (ESMs) have long been used to gain insight into the complex interactions and feedbacks within the Earth system that cannot be directly studied in laboratories or through observational datasets. They are particularly useful tools to investigate the response of the system to changes in external forcings, such as changes in the concentrations of greenhouse gases, that not only affect each of the components individually but also the interactions among the components. More recent Earth system model development efforts have focused on the representation of the interactive climate-chemistry system, with efforts like the Coupled Climate-Carbon Cycle Model Intercomparison Project (C4MIP, Friedlingstein *et al* 2006) or the estimation of the climate–carbon feedbacks using Earth system models of intermediate complexity (EMICs, Eby *et al* 2013).

ESMs have both advantages and limitations over detailed single component models. ESMs are computationally expensive. Because they simulate the global Earth system, they have not been the preferred modeling framework for targeted studies focusing on specific regions like Northern Eurasia when feedbacks are not considered. In addition, because ESMs represent the entire Earth system, with numerous interactions and feedbacks among components, simplifications in the representation of each component are necessary to keep the computational burden at reasonable levels. Thus, the representation of any particular component of the Earth system is rarely at the cutting edge. While their development relies heavily on detailed single-component models, the strength of ESMs is their capability to integrate a vast number of components. As a result, ESMs are well suited to investigate the complex feedbacks among processes and components of the Earth system at the local, regional and global scales. ESMs can also be used to investigate regional-to-global scale connections. An example of complex interactions and feedbacks that require an ESM is the effect of land-use change on climate.

Land-use change has been shown to have large impacts on the climate system, especially at local and regional scales (Brovkin *et al* 2006, 2013). Land-use change can affect the climate system via two pathways. First, land-use change impacts GHG concentrations in the atmosphere by changing land-atmosphere fluxes of carbon dioxide (CO_2), through land clearing mainly associated with deforestation, and nitrous oxide (N_2O), through changes in fertilizer application associated with the expansion and abandonment of cropland areas. This 'biogeochemical pathway' has a global fingerprint since GHGs are well-mixed in the atmosphere. Second, land-use change affects the physical characteristics of the land surface, including albedo, roughness and hydrology (e.g. evapotranspiration, soil moisture), and thus influence the exchange of heat and water between the land and the atmosphere. This 'biogeophysical pathway' has mainly a local and regional fingerprint, although it can affect regions away from land-use change through teleconnections in the climate system. An Earth system model, with its representation of the land, ocean and atmosphere components, including chemistry, aerosols and carbon cycle, is necessary to represent both feedback pathways (Hallgren *et al* 2013).

While many ESMs have recently incorporated the influence of land-use change on earth system processes in their simulations (Brovkin *et al* 2013, Eby *et al* 2013), the timing and locations of these land-use changes have been prescribed based on assumed economic decisions that were not affected by the simulated changes in environmental conditions. To better incorporate feedbacks of changing environmental conditions (particularly climate change) on future economic decisions, another suite of models are being developed, known as integrated assessment models, to represent the impacts of global change on the Earth system.

3.2. Integrated assessment models

The 21st century will bring unprecedented challenges including rapid population and economic growth, increasing demand for food, fiber, construction materials, energy and water at a time when emissions abatement targets, agreed to at the 21st Conference of the Parties (or 'COP21') to the United Nations Framework Convention on Climate Change (UNFCCC), will induce changes in the energy system away from fossil fuels and towards low-carbon alternatives, including biofuels and bioelectricity. Competition for land to meet these increased human demands will have major implications for land management practices, including water resources management, land-use change and land-use emissions (Melillo *et al* 2009, 2016, Reilly *et al* 2012), with potentially significant feedbacks to the climate system (Hallgren *et al* 2013, Jones *et al* 2013, DeLucia 2015). At the same time, GHG emissions will drive changes in temperature and precipitation patterns that will alter crop yields (Rosenzweig *et al* 2014, Sue Wing *et al* 2015), productivity of managed forests and natural terrestrial ecosystems, as well as the need for irrigation, and its costs and capacities. These changes will not only affect the food and water systems, but also the energy system (i.e. the Food-Energy-Water nexus) through impacts on the cost of growing biomass and water availability. The influence of growing populations, abating GHG emissions and climate change will differ regionally, and international trade in food and energy commodities can smooth impacts across regions.

A detailed representation of the human system, including the global economy, demography, technologies and user preferences, is essential to study potential impacts of future global change. While original climate change scenarios relied on $2{\times}CO_2$ concentrations idealized scenarios (first IPCC Assessment reports), future emissions of greenhouse gases and aerosols are now projected using integrated assessment models (IAMs). These models combine scientific and socio-economic modeling of climate change primarily for the purpose of examining the implications of climate mitigation and, to a lesser degree, potential pathways of adaption to climate change. IAMs generally include a model of the global economy that simulates anthropogenic emissions of greenhouse gas and a model of the physical climate system (e.g. Integrated Model to Assess the Greenhouse Effect or IMAGE, van Vuuren *et al* 2011b, MIT Integrated Global System Model or IGSM, Sokolov *et al* 2005, Reilly *et al* 2013, Global Change Assessment Model or GCAM, Thomson *et al* 2011, Model for Energy Supply Strategy Alternatives and their General Environmental Impact or MESSAGE, Riahi *et al* 2011, Asia Pacific Integrated Model or AIM, Fujimori *et al* 2014). Weyant *et al* (1996) identify three major goals of integrated assessment modeling: (1) to coordinate the exploration of the possible fate of both natural and human systems; (2) to support the development of climate policies; and (3) to identify research needs to improve our ability to design robust policy options. As highlighted in Weyant *et al* (1996), integrated assessment models are no stronger than the underlying natural and economic science that supports them. In addition, major inconsistencies exist in the different

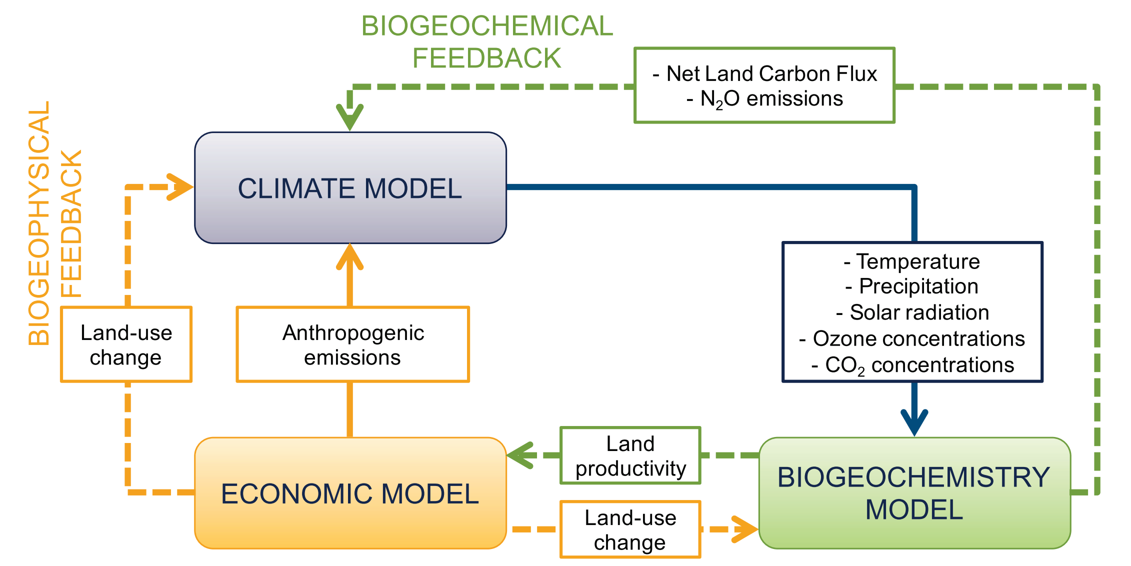

Figure 4. Schematic of modeling framework to investigate the biogeochemical and biogeophysical impacts of human-driven land-use change, similar to that used in Reilly *et al* (2012) and Hallgren *et al* (2013).

disciplines so the underlying science is often not in a form suitable for immediate use in IAMs. As a result, IAMs often lag the latest model development in an individual discipline. For example, the widely-used RCP scenarios, the underlying scenarios used as part of the latest IPCC Assessment Report, provide scenarios of anthropogenic emissions and concentrations as well as land-use change. However, the land-use change scenarios are driven only by economic considerations, assuming fixed land productivity, and thus do not account for climate change impacts on crop yields, natural terrestrial ecosystem productivity, or water availability for irrigation (Hurtt *et al* 2011).

Reilly *et al* (2013) suggest a different strategy for investigating the impacts of climate change on Earth's physical, biological and human resources and links to their socio-economic consequences in IAMs. The strategy relates changes in climate variables and human activities to changes in other physical and biological variables that affect human activities and well-being such as crop yield, food prices, premature death, flooding or drought events, and land-use change. Based on this strategy, various targeted studies have investigated land-use change using more detailed IAM frameworks. For example, Melillo *et al* (2009) use an IAM that accounts for the climate change impacts on management and natural terrestrial ecosystems to examine direct and indirect effects of possible land-use changes from an expanded global biofuel program on greenhouse gas emissions over the 21st century. Hallgren *et al* (2013) followed that work by investigating the climate impacts of a large-scale biofuels expansion, identifying the contributions of the biogeochemical and biogeophysical pathways (figure 4). Reilly *et al* (2012) use the same detailed IAM to explore the role of land-use change on global mitigation strategies to stabilize global warming to within 2 °C of the preindustrial level. While these modeling efforts highlight the potential capability of IAMs to enhance our representation of the coupled human–Earth system, here with a focus on land-use change, they represent state-of-the-art IAM modeling and, unfortunately, do not represent the general state of land-use change modeling in current IAMs. In addition, little information on Northern Eurasia can be gleaned from most IAM studies and IAMs are seldom used with a focus on Northern Eurasia. An exception is Kicklighter *et al* (2014), who extend the same detailed IAM model to include climate-induced vegetation shifts and investigate their potential influence on future land-use change and the associated land carbon fluxes in Northern Eurasia.

3.3. Global change modeling for Northern Eurasia

As the Northern Eurasia modeling community moves toward global change modeling studies with a major focus on the coupled human–Earth system, ESMs and IAMs can become valuable tools that quantify the relative importance of the responses of Northern Eurasian ecosystems and their feedbacks to the evolution of future global change. By examining interactions and feedbacks among Earth system and economic components, these models can expand upon existing research topics and open up new research avenues. We identify three different strategies revolving around these new approaches to global change modeling for Northern Eurasia that can benefit the NEESPI community:

- *Taking advantage of existing global change modeling efforts at the global level.* The ESM and IAM communities regularly participate in international coordinated modeling exercises to investigate varied global change research questions. For example, Nelson *et al* (2014a) examine the impact of climate change on agricultural production, cropland area, trade, and prices by climate, crop, and economic models. While these models are able to conduct simulations for various sized regions across the globe, these coordinated exercises generally lack a regional focus when publishing results, and usually do not identify Northern Eurasia as a key region of interest. Similarly, many global studies of the food–energy–water (FEW) system lack a focus on specific regions other than the United States, Europe, or China. Tighter collaborations of the NEESPI community with international coordinated exercises (e.g. AgMIP) could lead to major benefits for our understanding of FEW in Northern Eurasia and help identify any gaps in the representation of Northern Eurasia and its unique characteristics in ESMs and IAMs.

- *Developing coupled human–Earth system models specific to Northern Eurasia.* Various efforts to integrate the human system and the Earth system with a focus on Northern Eurasia already exist and must be continued and expanded upon. For example, a new coupled model, called WRF-Chem-DusMo (dust module), has recently been developed to explore the linkages among dust, climate and land-use change dynamics in Central Asia (Xi and Sokolik 2015, 2016). As indicated earlier, Earth system processes and economic activities tend to be represented rather simply in current ESMs and IAMs. Collaborations of the NEESPI community with coupled human–Earth system modelers could lead to improvements in the representation of Earth system processes and economic activities in Northern Eurasia in these models to the benefit of everyone.
- *Investigating tipping points specific to Northern Eurasia.* Major focus should be put toward identifying potential tipping points specific to the region, with implications for the global Earth system, such as permafrost degradation, the associated methane emissions and potential runaway climate change (Gao *et al* 2013); dieback of boreal forests from increasing heat and drought stress (Goetz *et al* 2007, Buermann *et al* 2014) and 'green desertification' caused by single or repeated catastrophic wildfires (Shvidenko *et al* 2011) and their potential to alter the global climate system through changes in greenhouse gases emissions and surface albedo. In addition, we argue that future research projects need to put a greater focus on understanding the varied and complex interactions among Northern Eurasia, surrounding regions and the rest of the world and identify how important these interactions are. Again, this can be achieved by relying on ESMs and IAMs, given that the appropriate improvements in the representation of key processes are made through collaborations between Earth system modelers and modeling experts from Northern Eurasia (e.g. improving the representation of permafrost or wildfires in ESMs).

Finally, we argue for a strong synergy between investigating the impact of global change on Northern Eurasia and better identifying the role of Northern Eurasia in the global system. To do so, strong collaborations between global and regional modeling teams are necessary and should be encouraged. We believe that ESMs and IAMs are particularly suited to investigate these regional interactions.

3.4. Data in support of global change modeling for Northern Eurasia

Similar to other modeling activities, the value of ESMs and IAMs to advance the understanding of key Earth system or economic processes in Northern Eurasia depends on the quality of data used to: 1) develop or update model algorithms and parameterizations; 2) provide inputs to drive model simulations; and 3) test model results. Useful data may be collected over a range of spatial and temporal scales such as site-level field observations and experiments, water quality data collected at the mouth of rivers that integrate information at a watershed scale, forest and soil inventories that integrate information at regional to country scales, economic data that integrate information at regional to country scales, and atmospheric chemistry flask data that integrate information at hemispheric to global scales (e.g. Krankina *et al* 2004, Houghton *et al* 2007, Prinn *et al* 2011, Kicklighter *et al* 2013, Liu *et al* 2013, 2014). In addition, gridded time-series data, based on either satellite and airborne remote imagery or interpolations among networks of site data, also provide useful information to evaluate how well ESM and IAM simulations capture spatial and temporal patterns (e.g. Liu *et al* 2013, 2014). However, there is still much uncertainty among gridded data sets representing an Earth system variable based on differing assumptions in interpolation procedures or interpretation of satellite imagery (e.g. Liu *et al* 2015). Additional efforts are needed to better understand and reduce these data uncertainties in the future.

It should come as no surprise that considerable amounts of data are required for evaluating the strengths and limitations of ESMs and IAMs for investigating global change over the Northern Eurasia as these models simulate a large number of components of the coupled human–Earth system. Due to the multidisciplinary aspect of the coupled human–Earth system, these datasets can be difficult to acquire, process and maintain in formats easily accessible to the whole research community. For Northern Eurasia, many satellite data products are publicly available (i.e. NASA and NOAA or the ESA

Living Planet Programme and the COPERNICUS programme https://earth.esa.int/web/guest/data-access), and have been used by the NEESPI research community to study, among others, the carbon cycle, land cover, land use, and forest fire monitoring. In addition, diverse datasets have been developed over the last decade to support the NEESPI domain modeling. These include, but are not limited to:

- Meteorological data (observations and some model products) for Northern Eurasia are available (with data overlaps) from three national data centers. While these data centers are 'national', each center carries a suite of information for either the entire NEESPI domain or most of the domain as well as for the Globe. These are the Russian Center for Hydrometeorological Information-World Data Center, RIHMI-WDC (http://meteo.ru/english/data/), the Beijing Climate Center (http://bcc.cma.gov.cn), the US National Center for Environmental Information (www.ncei.noaa.gov/access) and the European Climate Research Unit (e.g. CRU TS Version 3.22 and TS 4.0; www.cru.uea.ac.uk/data).
- Hydrological and geomorphological information for Northern Eurasia is stored and updated at the NEESPI Focus Research Center for Water System Studies at the Department of Geography of the University of New Hampshire (www.wsag.unh.edu/neespi.html). Examples of products available from this Center can be seen at: http://neespi.sr.unh.edu/maps/.
- Land cover information for the NEESPI domain became a part of the GOFC-GOLD data holdings www.gofcgold.wur.nl/sites/neespi.php. For Northern Eurasia, these data holdings serve as a depository for the needs of the forest monitoring and full carbon budget accounting of the region. The NASA data holding for satellite products (https://mirador.gsfc.nasa.gov/) also includes Northern Eurasia. The ESA Living Planet Programme with COPERNICUS offers also freely available satellite data over Northern Eurasia (e.g. Sentinel data; www.esa.int/Our_Activities/Observing_the_Earth/Copernicus).

Furthermore, many information systems have been developed over the years by the NEESPI community (e.g. Leptoukh *et al* 2007, Titov *et al* 2009, Gordov *et al* 2013). These tools include storage and processing models for climate datasets (Okladnikov *et al* 2016), an online instrument for multidisciplinary data visualization, analysis and manipulation with a focus on hydrological application (Shiklomanov *et al* 2016), and a hardware and software platform prototype for monitoring and projecting environmental changes in the northern extratropical areas (Gordov *et al* 2016). These powerful interactive visualization and analysis tools provide access to climate datasets to researchers and users without requiring expert knowledge in data processing and plotting. As such, they serve an important mission to broaden the Northern Eurasia research community.

Similarly, socio-economic data are available for many countries within Northern Eurasia and the globe. In particular, the Global Trade Analysis Project (GTAP) dataset (Aguiar *et al* 2016) contains the consistent representation of economic output, trade, consumption and government expenditures that cover the entire economies of the following countries: Norway, Sweden, Finland, Russia, Mongolia, China, Kazakhstan, Azerbaijan, Georgia, Armenia, Ukraine, Bulgaria, Romania, Hungary, Czech Republic, Slovakia, Poland, Belarus, Lithuania, Latvia, and Estonia. Land-use data and energy data are available from the major agencies like the International Energy Agency (IEA) and Food and Agriculture Organization (FAO). For many of these countries, regional representation is also available. For example, Tarr *et al* (2001) provide the social accounting matrices for 88 regions of Russia with data for production, consumption and intermediate use of commodities and services, and for bilateral trade with other regions and the rest of the world. The economy in each Russian region is represented by 30 industrial sectors producing commodities and services.

At the same time, there is a need for improvement in the availability and quality of both Earth system and socio-economic data. Networks of Earth system observing stations, such as meteorological stations, are quite dense in the populated regions of Northern Eurasia but they are scarce over the desert regions to the south, the mountains of western China and northern Siberia. Since the availability and quality of observational data from these networks varies dramatically, and since international archives are updated only intermittently over these regions, it is advisable to collaborate with local scientists, especially in China and the Central Asian newly independent states. Furthermore, while most country-level economic transactions are available for analysis, the disaggregation of the data at a finer spatial scale is limited. Even more limited are data for socio-economic characteristics like level of education, health services, employment numbers by industry, income by different age, gender or location, population migration, etc.

For these reasons, the global change modeling community must be an essential driver to help identify the crucial data gaps and to provide guidance to research agencies about the type of data needed to support global change modeling. Those include statistical agencies, who would benefit from information on the data required for the analysis of the economic and welfare implications of global change at a level that is useful for decision-making. They also include science agencies, who need to know what data would be required, for example, to improve models of permafrost degradation and its associated methane emissions.

4. Emerging issues in the coupled human–Earth system of Northern Eurasia

At the frontier of Earth system and integrated assessment modeling, many issues and research foci have recently emerged and driven further development of coupled human–Earth system models. In this section, we highlight a few important emerging issues in the coupled human–Earth system of Northern Eurasia.

While modeling of the FEW nexus has gained substantial momentum in recent years, it is still arguably an emerging issue for most research groups, even when not focusing on Northern Eurasia. Major innovations at the nexus of the FEW system are still needed, with improved integrations of the various components of the coupled human–Earth system. Currently, well-recognized studies of the FEW system (Elliott *et al* 2014, Nelson *et al* 2014a, 2014b, Schmitz *et al* 2014, Valin *et al* 2014, von Lampe *et al* 2014) have common limitations: they impose climate change without considering potential feedbacks of the FEW system to the regional and global climate through either biogeochemical and biogeophysical pathways; they fail to fully integrate all three components of the FEW system and their interactions, such as not accounting for the impact of water scarcity on irrigation availability and its impact on irrigated crop yields or on water availability for power plant cooling and its impact on energy production; and they fail to account for even simple adaptive management practices, such as improvements in conveyance efficiency, field efficiency and water storage for irrigation. Certainly, improving the integration of the FEW system within IAMs is underway but these modeling development efforts have not yet focused on Northern Eurasia and its unique environmental and socioeconomic background. While the FEW nexus is a global issue, it has unique characteristics in different regions (Lawford *et al* 2013). For the NEESPI region, unique characteristics include thermokarst dynamics, permafrost degradation, scarcity of human infrastructure, varied levels of agriculture development and management practices, locally diverse hydrological conditions associated with complex biomes and climate interactions. These characteristics need to be understood and modeled at appropriate scales. Better data and information are urgently needed to improve the effective use of information and models in support of better planning and decision-making in the region.

With air pollution identified as the world's largest environmental health risk (Lim *et al* 2012), many research groups have developed modeling frameworks that link climate change, air pollution and human health (West *et al* 2007, Jacobson 2008, Selin *et al* 2009). These modeling frameworks have been used to estimate the economic implications of changes in air quality (Fann *et al* 2014) as well as to evaluate the air quality co-benefits of climate policies and improve climate change policymaking (Nemet *et al* 2010). However, such studies have largely focused on countries like the United States (Thompson *et al* 2014, Saari *et al* 2014, Garcia-Menendez *et al* 2015), despite the importance of the air pollution and health nexus in Northern Eurasia and its unique characteristics. Aside from the traditional anthropogenic precursor emissions associated with the industry, energy and transportation sectors, or biogenic emissions of precursors, Northern Eurasia experiences varied and complex sources of air pollution, including wildfires, crop residue burning and dust. With Russia expected to experience the largest increase in burned forest area in the world (Kim *et al* 2017), the resulting emissions of particulate matter are likely to play a considerable role in future changes in air pollution and health. Meanwhile, the Russian Federation accounted for 31%–36% of all cropland burning across the globe between 2001 and 2003 (Korontzi *et al* 2006), with crop residues being burned to clear fields, fertilize the soil, and eliminate pests and weeds. Finally, the drylands of Central Asia, which is the largest dry area in the extratropics, is a major source of dust storms and a powerful source of atmospheric pollution (Issanova and Abuduwaili 2017). In addition to these pollution sources, complex transport of air pollutants to and from Northern Eurasia need to be better understood. Quantifying the economic impact of future changes in air pollution in the region, especially taking into account these unique sources of pollutants and the transport of pollutants to and from surrounding countries, can prove key to accurately inform policy responses for Northern Eurasia.

Beyond existing issues like the fate of FEW system or the air quality and health nexus, Northern Eurasia could experience climate-induced changes in coming years that may well reshape the region. As the Arctic sea ice extent shrinks, Arctic trade routes will remain open for longer periods of time, and new routes will likely open. Investigating the fate of Northern Eurasia as these new trade routes emerge will require complex coupled human–Earth system models that account for the many potential impacts, interactions and feedbacks on the system. Combined with increasing demand for natural resources from neighboring regions like India, China and other Southeast Asian countries, these new trade routes could result in the ability of the timber industry and energy exploration to reach remote areas like Siberia. At the same time, warmer temperatures could cause the disappearance of temporary roads constructed over frozen lakes and rivers, thus requiring major developments in infrastructures, including highways and communications (Stephenson *et al* 2011). As these changes create new

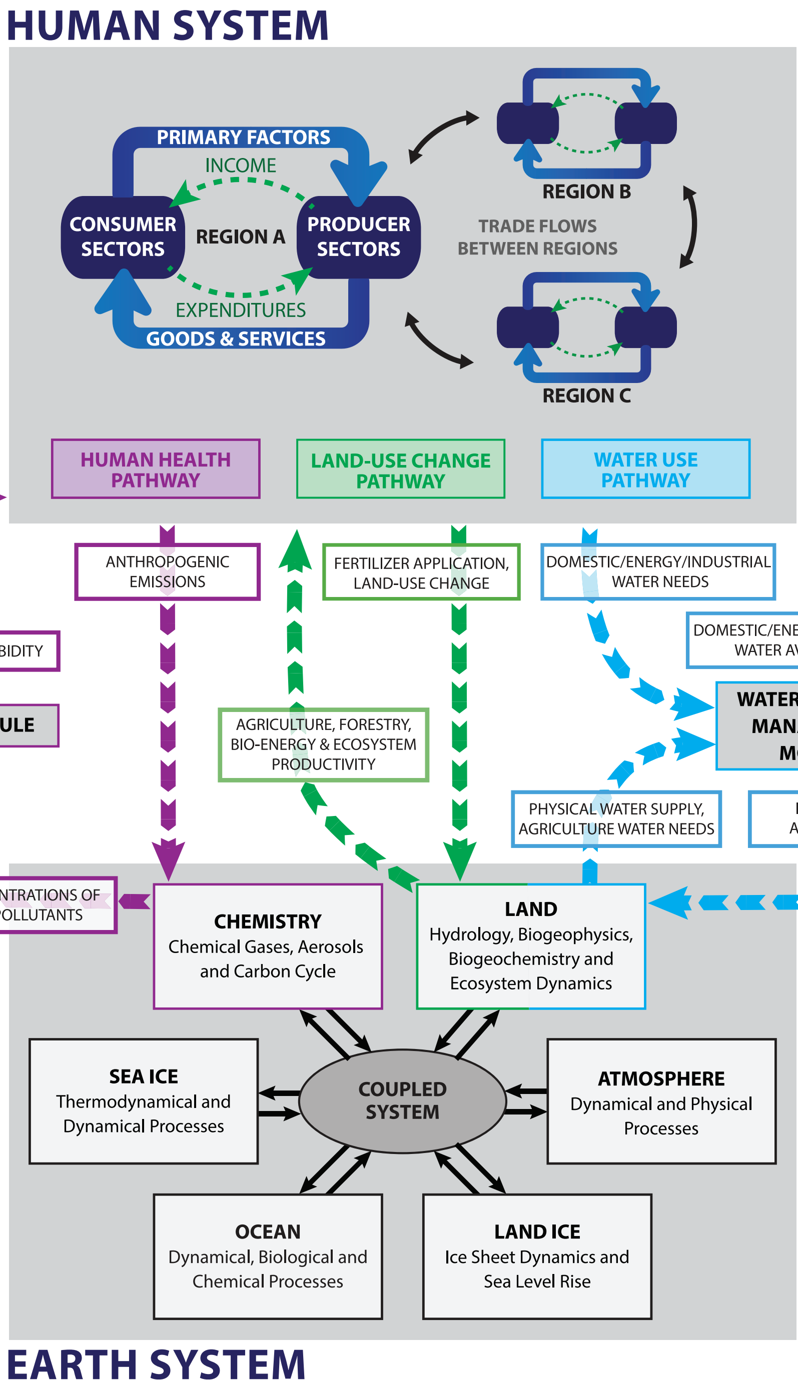

Figure 5. Schematic of an integrated assessment model (IAM) that couples a human activity model and an Earth system model with a focus on three feedback pathways: health, land-use change, and water resources.

economic opportunities, significant population migration within Northern Eurasia and from neighboring regions could create new socio-economic stressors. Furthermore, with increasing population and demand for energy, along with permafrost degradation that impacts buildings in many communities in Siberia, major changes in urbanization, both expansion and abandonment (including 'boom and bust'), and infrastructure (oil and gas) can be expected. The implications for land-use change in Northern Eurasia could be substantial.

There are many other examples of complex pathways of interactions and feedbacks between the human system and the Earth system that are yet to be investigated and that could prove very important for Northern Eurasia. Models that include a detailed representation of all components of the human–Earth coupled system, while accounting for the exhaustive number of feedbacks among these components, can certainly provide tremendous and novel insights into the complex issue of global change. An example of such a model, with a focus on three feedback pathways, water resources, health, and land-use change, is shown in figure 5.

Given the imperfect nature of models, large uncertainties in future projections of major driving forces of change (i.e. demography, economic growth, the implementation of climate policies, and the development of new technologies to name a few), and our limited knowledge of various processes (i.e. climate system response, natural climate variability, ecosystem dynamics), studies need to be placed in the context of uncertainty (Sokolov *et al* 2009, Webster *et al* 2012, Monier *et al* 2013). Large model intercomparison exercises are growing steadily to better understand model structural uncertainty, although few have a focus on Northern Eurasia (Rawlins *et al* 2015). The implementation of large ensembles of model simulations is fast becoming the norm and studies using only a single model have been slowly marginalized. At the same time, the reliance of the community on standard scenarios and model simulations, such as the RCPs and the CMIP5, can lead to a false sense of confidence in the full distribution of future global change. For this reason, coordination of research efforts and explicit guidelines for modeling global change can be beneficial to the community, but only if they do not preclude the diversity of models, approaches, and focus studies.

5. Final words

Since the beginning of the NEESPI project over a decade ago, scientists from multiple disciplines and nations have provided a truly interdisciplinary and dynamic body of research. They highlighted major past and ongoing environmental, socioeconomic and climatic changes over Northern Eurasia and investigate their impacts to natural ecosystems and society. To support their research, they developed a large number of models to organize and improve our understanding of the state and dynamics of terrestrial ecosystems in northern Eurasia and their interactions with the Earth system. These models have been important tools to enhance our scientific knowledge and predictive capabilities to support informed decision-making.

Many of the new international programs are emphasizing resilience and transformation of human/environmental systems in the face of environmental change. NEESPI has great reason to be proud of its success. This review provides but a glimpse of what has been accomplished in observing, understanding and modeling a region undergoing significant environmental, socioeconomic and climatic changes. Nonetheless significant work remains to be done in the continued improvement of our modeling capability to represent the coupled human–Earth system in Northern Eurasia in the face of global change. In this review, we argue that Earth system models and integrated assessment models exemplify new approaches to accomplish that objective. At the same time, we recognize that to succeed in making ESMs and IAMs valuable tools for Northern Eurasia, their representations of the unique characteristics of Northern Eurasia need to improve. This can only be achieved through tight collaborations between the Northern Eurasia modeling community and the ESM and IAM communities.

The International Geosphere Biosphere Programme (IGBP) officially ended in December 2015 after 30 years of success and many of its components transformed into the 'Future Earth' Secretariat. As a result, the NEESPI project is moving to establish a new program, '*Northern Eurasia Future Initiative*' (NEFI), with the goal to better represent the coupled human–Earth system to model global change for Northern Eurasia. The future program strongly depends on building an understanding of how human populations will be affected by environmental changes across the region, what management practices can be developed to help mitigate or allow adaptation to these changes, and how we can bridge the considerable gaps in research procedures, national scale policy intervention, capacity for prediction, and time- and space- scales that can plague the incorporation of human dynamics with environment dynamics. Thus, NEFI is a logical consequence of the accomplishments of NEESPI.

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